Quantifying Variation in Canopy Height from LiDAR Data as a Function of Altitude Along Alpine Treeline Ecotone in Indian Himalaya

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Abstract

Canopy height is a key physiognomic parameter of biodiversity, productivity and other ecosystem functions in high-elevation alpine ecosystems. However, little is known as to how altitude influences canopy height in these ecosystems. This study makes use of an open-access global forest canopy height map with a spatial resolution of 30 m that integrates Global Ecosystem Dynamics Investigation (GEDI)–Light Detection and Ranging (LiDAR) data (April–October 2019) and Landsat analysis-ready time-series data (year 2019). The variation in canopy height was quantified for each 100 m elevation band starting 500 metres below the alpine treeline ecotone at 3780 masl and extending up to 500 m above the alpine treeline ecotone. The global forest height map was compared to the in situ data (root-mean-square error [RMSE] = 6.6 m; mean absolute error [MAE] =

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4.45 m). We observed a strong negative correlation ($R^2 = 0.96$) between altitude and LiDAR-estimated canopy height. The altitude alone explained 96% of the variation in canopy height ($p < 0.001$). This chapter provides the first of its kind landscape-level quantification of the rate at which canopy height decreases with the increase in altitudinal gradient across the Indian Himalayan treeline.

Keywords

Alpine ecosystem · Canopy height · GEDI LiDAR · Indian Himalayan region · Treeline ecotone

8.1 Introduction

In recent decades, Himalaya has experienced the most rapid climate warming (Field et al. 2014) along with an increase in extreme climate events (Shrestha et al. 2012). The pristine environment with the least amount of anthropogenic activities makes it an ideal 'natural laboratory' to study tree growth responses in altitude-mediated thermal compression regime. Owing to heat deficiency, tree development at high altitude is predicted to be more vulnerable to climate change (Körner and Paulsen 2004), which in turn will alter the forest ecosystem composition and functioning (Körner 2012). As a result of the ongoing rapid warming, tree growth may respond by upward shifting of treeline (Grabherr et al. 1994) and enhanced tree growth (Shi et al. 2020).

Altitude is a strong limiting factor for the tree growth enhancement in mountainous areas since the height of trees is affected by decreasing temperatures with increasing altitude. This phenomenon results in shorter growth and peculiar formations at the treeline, i.e. the altitudinal limit of tree growth (Körner 2012). However, little is known about role of altitude in regulating canopy height in these ecosystems at a landscape scale. Therefore, it is critical to understand altitude-dependent canopy height responses and their spatial patterns at a landscape scale. Quantifying tree height along altitudinal gradients aids in understanding of climate-driven tree patterns and their climate sensitivity to continuing climate change. Quantifying canopy height along altitudinal gradients aids in understanding of tree growth sensitivity to ongoing climate change. Canopy height dynamics of the alpine ecosystem of Himalaya has rarely been studied, and the present study, therefore, addresses this research gap. We compiled canopy height data at treeline in Indian Himalaya to analyse spatial variations in climate-driven canopy height patterns.

Traditionally, canopy height is acquired directly through field measurements *or* indirectly through two-dimensional (2-D) image information. However, these methods are expensive and impractical for landscape-level studies. The new generation of active remote sensing technologies like Light Detection and Ranging (LiDAR) system provides direct, three-dimensional (3-D) measurement of the vertical structure of vegetation and terrain surface. The most recent space-borne LiDAR instrument is National Aeronautics and Space Administration's (NASA's) Global

Ecosystem Dynamics Investigation (GEDI). It is designed to give information about forest vertical structure through application of GEDI, and it is anticipated to acquire 4% of Earth's land surface over its 2-year nominal mission. It gives information about canopy height, canopy cover, plant area index and topography (Dubayah et al. 2020). For practical applications, standard GEDI data packages have significant restrictions. Since GEDI data provide footprint-level products (average footprint 25 m) represented by a point sample, leaving considerable land surface without observations, GEDI's transect sampling may not be appropriate for quantifying variation in canopy height over the study area. Potapov et al. (2021) developed the global forest height map by integrating GEDI-derived canopy height measurements with Landsat multi-temporal surface reflectance data. To achieve high-quality forest height estimation, this open-access global forest canopy height map was used for the study.

Here, we quantified the variation in canopy height for each 100 m elevation band starting from 500 m below the treeline to 500 m above the treeline. Continuous datasets at large geographic extents allowed us to identify the relationship between altitude and canopy height at a landscape level. Specifically, in this study, we addressed the following questions: (a) What is the canopy height of the alpine treeline ecotone along parts of the Indian Himalaya? (b) Are the variations in canopy height at treeline similar with respect to altitude from west to east? (c) Does other physiographic factors such as latitude have relationship with canopy height?

8.2 Study Area

The study area includes the part of Indian Himalayan region featuring highly heterogeneous terrain and dense forest (Fig. 8.1). This includes five Indian Himalayan states, viz. Jammu and Kashmir (J and K), Himachal Pradesh (H.P.), Uttarakhand, Sikkim, and Arunachal Pradesh (A.P.). Because of the complex three-dimensional geo-ecological variability with diverse thermal and biotic variables, Himalayan treeline ecotones display significant differences in physiognomy and altitudinal position (Schickhoff 2005). In the Himalaya, climate is strongly regulated by altitude, resulting in steep environmental gradients. The region's microclimatic variability leads to significant variations in vegetation over short distances. Heavy and long-duration precipitation in both winter and summer leads to luxuriant vegetation and regions of diverse biological communities with a high level of endemism. The competitive ability of evergreen trees and large shrubs of the genus *Rhododendron*, which have replaced the deciduous birch belt in the eastern Himalaya, increases along the northwest–southeast gradient due to strongly decreasing temperature during winter months and increasing humidity during monsoon months along the gradient (Schickhoff et al. 2015).

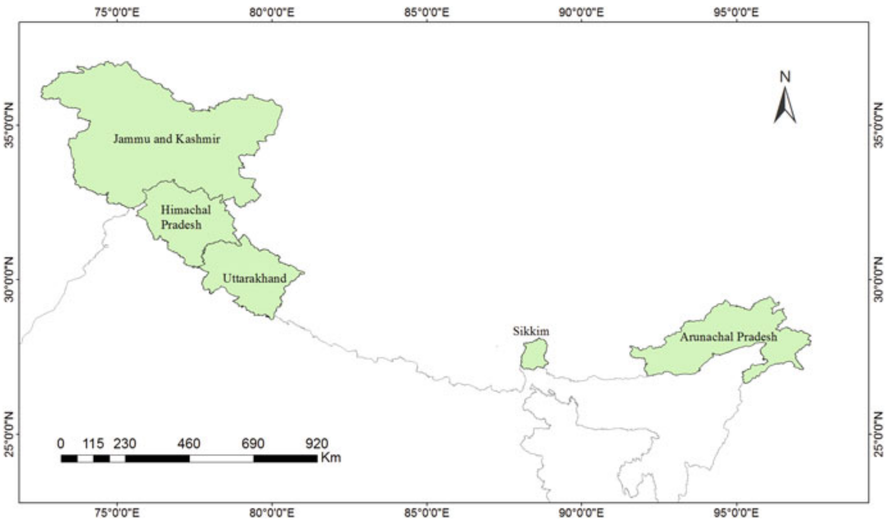

Fig. 8.1 Study area (shown in shade)

8.3 Data Used

8.3.1 Global Forest Canopy Height Map

The global forest canopy height map of 30 m spatial resolution was acquired from Global Land Analysis and Discover-University of Maryland (UMD-GLAD) website https://glad.umd.edu/dataset/gedi. The global forest height map was developed by integrating GEDI-derived canopy height measurements with Landsat multi-temporal surface reflectance data (Potapov et al. 2021). The dependent variable for model calibration was the relative height at 95% and the independent variable was the Landsat multi-temporal metrics obtained from the analysis-ready data (GLAD ARD) time-series. The global canopy height map for selected Himalayan states under the study is shown in Fig. 8.2.

8.3.2 Treeline Data

The treeline position delineation was acquired from the previous research carried on the alpine ecosystems by Singh et al. (2021), where the authors have used Cloud-free, terrain corrected, ortho-rectified (Universal Transverse Mercator World Geodetic System-1984 projection) Resourcesat-1/2 Linear Imaging Self Scanning Sensor (LISS-III) multispectral images to delineate alpine treeline over the Indian Himalayan region. The details of the data used are given in Table 8.1. First digital numbers (DNs) in the multispectral images were converted to radiance using the equation given by Chander and Markham (2003). This was atmospherically

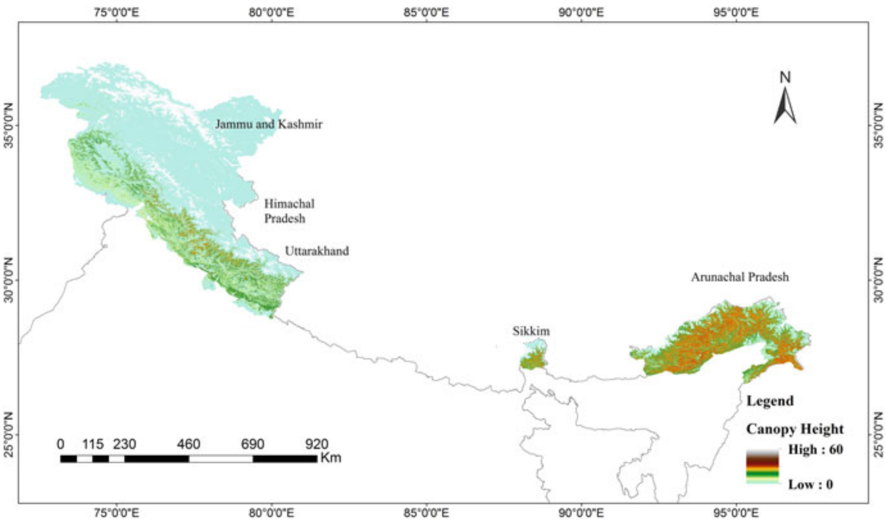

Fig. 8.2 Global forest canopy height map. Pixel values ranging from 0 to 60 represent forest canopy height in metres. (Downloaded from website https://glad.umd.edu/dataset/gedi)

Table 8.1 Satellite data used for treeline delineation

Sr. No	Himalayan state	No. of scenes	Month/year range
1	Jammu and Kashmir	31	August–December, 2012–2014
2	Himachal Pradesh	6	October–November, 2014
3	Uttarakhand	10	October–December, 2012–2014
4	Sikkim	4	November–December, 2012–2014
5	Arunachal Pradesh	13	October–December, 2012–2014

Source: Singh et al. (2021)

corrected using the Fast Line-of-Sight Atmospheric Analysis of Spectral Hypercube (FLAASH) technique in the Environment for Visualising Images (ENVI) software. The automatic contour delineation method in Aeronautical Reconnaissance Coverage Geographic Information System (ArcGIS) (ESRI 2016) was used to delineate the treeline. Figure 8.3 shows the treeline position delineation of Himalayan states under the study.

8.4 Methodology

8.4.1 Quantification of Canopy Height

The height map was downloaded in GeoTiff format. The pixel values representing canopy heights in the raster data were extracted to station points generated over the alpine treeline vector and buffer around it (100 m and 500 m) along with the information about geolocation as attributes.

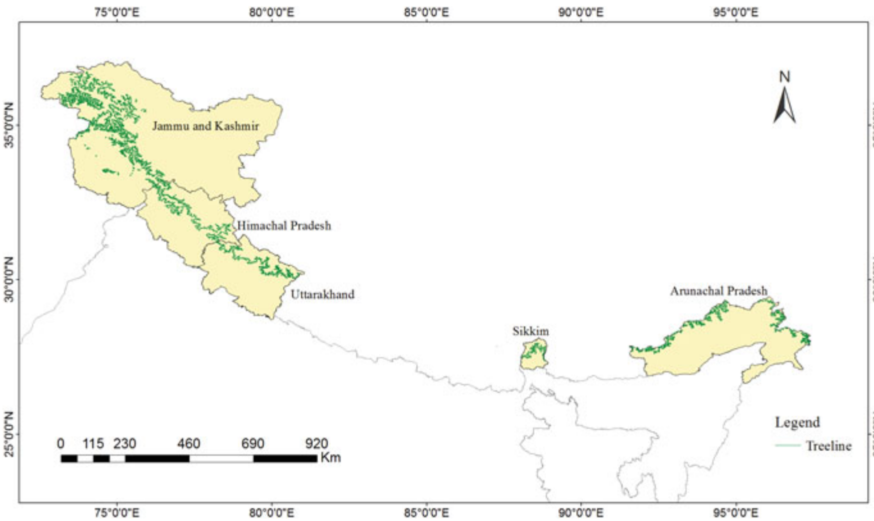

Fig. 8.3 Alpine treeline ecotone position in Indian Himalaya. (Adapted from Singh et al. 2021)

A shapefile of the buffer zone was created around the treeline and it extends between 500 m altitude below and above the treeline location. The shapefile was created in ArcGIS (ESRI 2016) in such a way that in every 100 m altitude a distinct buffer zone was formed. The average canopy height was calculated for each 100 m altitudinal group. The variation in canopy height as a function of altitude was quantified using Pearson's correlation coefficient (also known as Pearson *R*-test) represented by '*r*' and coefficient of determination (COD), i.e. square of '*r*', represented by 'R^2'. '*r*' was computed using the following formula:

$$r = \frac{n\left(\sum xy\right) - \left(\sum x\right)\left(\sum y\right)}{\sqrt{\left[n\sum x^2 - \left(\sum x\right)^2\right]\left[n\sum y^2 - \left(\sum y\right)^2\right]}}$$

where x and y are two different variables and n is the number of observations.

8.4.2 Ground Survey and Validation

Field validations were conducted in Jammu and Kashmir (74°20′ E; 34°01′ N) and Himachal Pradesh (77°57′ E; 31°14′ N). Endemic alpine tree species are abundant in these regions. The vegetation varies from closed montane forest to high-elevation alpine meadows across the elevation gradient. Anthropogenic activities have little influence on these areas. Canopy heights were collected from a sample plot of size 400 m^2 (20 m × 20 m) in Jammu and Kashmir and Himachal Pradesh in elevations ranging from 3345–3540 m and 2469–3719 m, respectively. The height of each tree was calculated with a clinometer using angles measured after walking 10 m from the base of the tree. The average canopy height of each sample plot (37 points) is treated as a training point for the validation of the satellite-derived treeline canopy height. The elevation and geolocations of the treeline species were noted along the altitudinal gradient.

The global forest canopy height map and ground measured canopy heights were compared using the statistical indices: mean absolute error (MAE), and root-mean-square error (RMSE). These indices, which are checked for goodness-of-fit, are defined as follows:

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\mathrm{S}-\mathrm{I})^2}$$

$$\mathrm{MAE} = \frac{1}{N}\sum_{i=1}^{N}|\mathrm{S}-\mathrm{I}|$$

where S stands for satellite observations, I for in situ observations and N is the number of points.

8.5 Results

Scatter plots of in situ observations of canopy height and satellite-derived canopy height from global forest height map is shown in Fig. 8.4. It is observed that MAE and RMSE for the global forest height map are 4.23 m and 5.23 m, respectively. Further, a significant correlation (correlation coefficient = 0.63) is also found

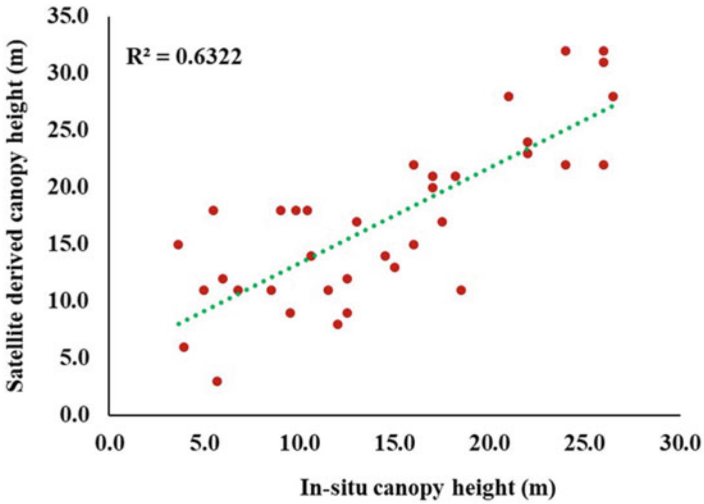

Fig. 8.4 Scatter plots of satellite-derived canopy height against in situ datasets

between ground measured and satellite-derived canopy heights ($p < 0.001$). The significant correlation and minimum MAE and RMSE provide high confidence for utilization of the global forest height map. Ground truth observations compared with satellite-derived canopy height are shown in Fig. 8.4.

8.5.1 Response of Canopy Height to Altitude

Estimation of canopy height varied between 3 m and 41 m along alpine treeline ecotone in Indian Himalaya. We observed a clear, strong negative response ($R^2 = 0.96$) of canopy height to increasing altitude and around 96% of the variability in mean canopy height is explained by altitude ($p < 0.001$). The correlation between canopy height and altitude is shown in Fig. 8.5. Canopy height decreased at a rate of 0.4 m per 100 m altitude. Along the altitudinal gradient, canopy height decreased from 12.42 ± 6.81 m to 8.84 ± 4.48 m.

8.5.2 Relationship Between Canopy Height and Treeline in Himalaya

Canopy height gets shortened at 0.3 m per 100 m starting from 500 m below the treeline to 500 m above the treeline in Jammu and Kashmir; 0.5 m in Himachal Pradesh; 0.7 m in Uttarakhand; and 0.4 m in Sikkim and Arunachal Pradesh. The results are shown in Fig. 8.6. As calculated from Cartosat-1 DEM, the mean

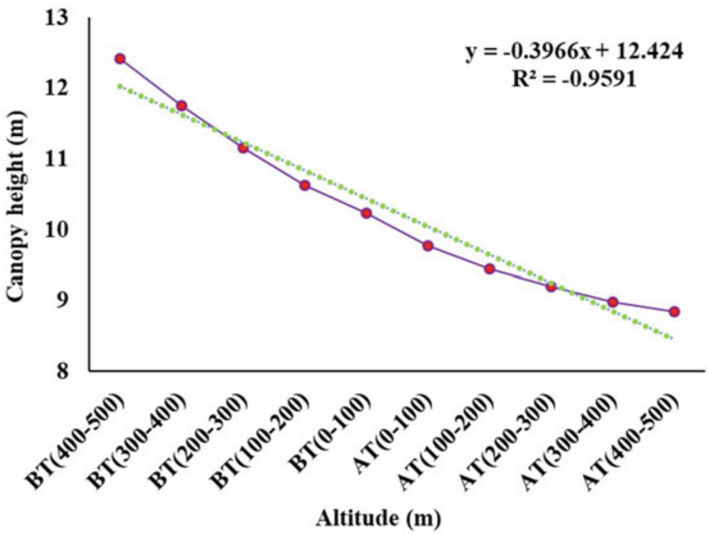

Fig. 8.5 Relationship between altitude and canopy height in the Indian Himalayan alpine treeline ecotone. The blue line represents the trend line. R^2 for the model is calculated as the coefficient of determination of the relationship between the altitude and canopy height

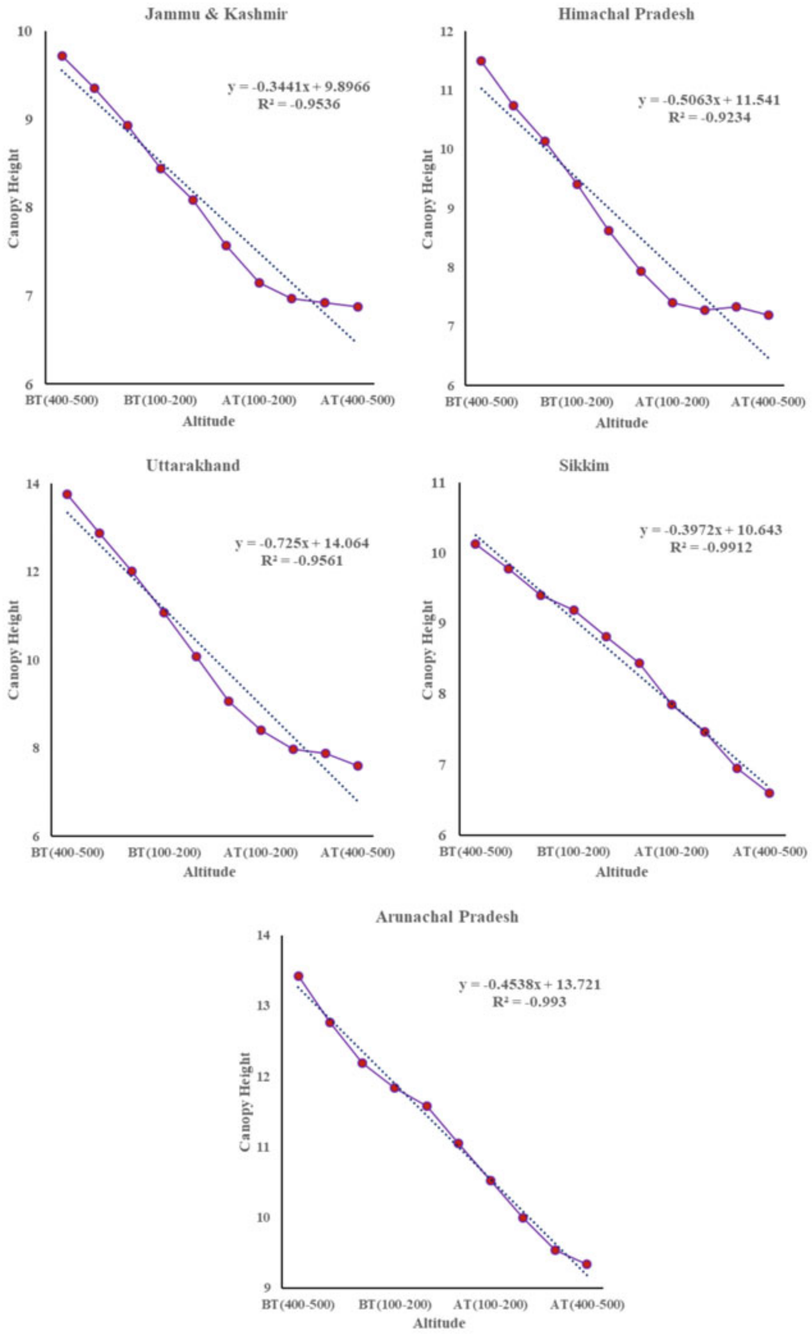

Fig. 8.6 Relationship between altitude and canopy height in Jammu and Kashmir, Himachal Pradesh, Uttarakhand, Sikkim and Arunachal Pradesh

elevation of the treeline in Jammu and Kashmir, Himachal Pradesh, Uttarakhand, Sikkim and Arunachal Pradesh Himalaya was 4121 m, 3520 m, 3615 m, 3542 m and 4136 m, respectively (Singh et al. 2021).

8.6 Discussion

8.6.1 Canopy Height Decreases with Altitude

The declining trend in canopy height with increasing altitude is in agreement with reports from other areas (Wang et al. 2012; Paulsen et al. 2000; Liang et al. 2011). The reduction in canopy height may be interpreted as direct feedback to decreasing temperature with increasing altitude (Körner 1998, 2012; Wieser and Tausz 2007; Holtmeier 2009). The variations in canopy height show how trees respond to climatic factors (temperature, wind and moisture) in a natural environment, and help in the study of processes that limit tree growth. The height of trees increases, where stresses are minimal and resources are abundant (King 1990; Cary and Pittermann 2018). The individual canopy height is known to be influenced by climatic and soil conditions, terrain, vertical vegetation structure and light competition (Zhang et al. 2016). The physiological processes essential for tissue formation, including photosynthesis, respiration, food allocation and shoot growth, are limited by the low temperature at high altitudes (Koch et al. 2004).

The reduction in canopy height points to the stress along the altitudinal transect, which is marked by a strong temperature decrement. Environmental factors, such as low temperature, caused water stress, and poor nutrient availability impacted the tree performance at high altitudes (Körner 2003). Previous studies on mountainous biomes present significant role of hydraulic limit in canopy height (Klein et al. 2015; Tao et al. 2016; Petit et al. 2011). Wang et al. (2012) present strong evidence of the dominant role of low temperature-induced water uptake, along with gravity, in limiting canopy height. In our case, the adiabatic gradient, i.e. the reduction in temperature with altitude, appears to be the major cause of the decrease in canopy height with altitude. In a modelling study, Ameztegui et al. (2021) reported that the relationship between elevation and maximum canopy height is not progressive; however, it begins at a specified location below the treeline but above the trailing limit of the species' range. Other characteristics such as slope, direction or dominant tree species showed no effect on the negative correlation.

8.6.2 Canopy Height Decrement Patterns Along Himalayan Arc

It is clearly observed that canopy height decrement with respect to altitude declines from west to east within Himalayan arc. Western Himalayan states (Himachal Pradesh and Uttarakhand) show a relatively higher rate of change in canopy height with respect to altitude than eastern Himalayan states (Sikkim and Arunachal Pradesh). It is apparent that ecological processes in mountains are influenced not by elevation alone, but by a variety of other variables too (Körner and Spehn 2019). The Himalayan arc takes a latitudinal dip in its middle part (Nepal) as it advances from northwest to southeast, and the extreme southeast end is at lower latitudes than the northwest end. A previous study conducted on the global variation of forest canopy height reported that maximum canopy height is inversely proportional to latitude (Zhang et al. 2016). The decreasing trend of canopy height decrement may be due to the decrease in latitude as we go from the northwest to the southeast. A 1° latitude increase results in a 0.55 °C drop in mean yearly temperature. As a result, temperatures at a given elevation are more likely to be warmer towards the southeast end than the northwest end.

Large amounts of rainfall are there on the windward slopes of the eastern Himalaya as a result of the south Asian monsoon, while staggered mountain ranges function as climate barriers, preventing moisture-bearing monsoonal air masses from reaching the western Himalaya, where moisture air masses are only brought in by minor monsoons from the Arabian Sea. The climate in the western Himalaya is drier with less precipitation, whereas the climate in the eastern Himalaya is dominated by a heavy moist climate with heavy precipitation (Schickhoff et al. 2015). From east to west and from low elevation to high elevation, moisture decreases (Singh et al. 2017). Studies have also reported that the temperature lapse rate declines from west to east for treeline transect, i.e. from less moist to high moist sites in Himalaya. A previous study carried out in treeline transect has reported lower temperature lapse rate value in Uttarakhand Himalaya (Joshi et al. 2018). Thus, along the northwest–southeast gradient, strongly decreasing winter cold and higher monsoonal humidity levels increase the maritime climatic conditions for trees to grow taller and result in lower canopy height reduction in eastern Himalayan states.

8.7 Conclusion

Our study is the first landscape analysis of the relationship between altitude and canopy height over the Indian Himalayan alpine ecotone. With the canopy height information, we were able to address fundamental questions about how canopy height varies with increase in altitude, and provide evidence of the existence of a significant negative response. The altitude–canopy height relationship has the prospect of becoming a fundamental tool in the study of responses of mountain trees to environmental changes. Our results reveal that the height response of treeline trees spatially varies along Indian Himalayan arc in response to varying environmental factors and this will have a bearing in future climate change scenarios as well. Finally, GEDI (Global Ecosystem Dynamics Investigation)-derived parameters such as total canopy cover, total plant area index, foliage height diversity index, foliage clumping index and volumetric scattering coefficient of the canopy open a promising future for evaluating the relationship between tree physiognomic parameters and climatic variables at the global scale.

The present study advocates the use of the canopy height–altitude model to further study the carbon sequestration patterns in the light of changing climate. The Dynamic Global Vegetation Model (DGVM) can be set up to simulate shifts in potential vegetation and its associated biogeochemical and hydrological cycles as a response to shifts in climate. DGVMs require realistic initial values and when we run it in a spatially distributed mode, we generally assume to have homogeneous (default) conditions within each cell as far as canopy height is concerned. Now, with the available canopy height–altitude model we can have dynamic heights for Indian Himalayan region as an input to the DGVM. However, more accurate and fine-resolution data will be required to achieve more consistent estimates of various ecosystem parameters.

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